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DEVICE, IN PARTICULAR FOR BISTATIC RADAR APPLICATIONS

The present invention is directed to a device for bistatic radar applications, in particular.

The fundamental method of functioning of pulsed radars for measuring the distance and velocity of objects that is valid to this day, had already been described in 1938 by Col. William Blair of the U.S. Signal Corps. When a microwave carrier undergoes pulse modulation, a signal of a defined pulse duration T_p is periodically transmitted at the pulse repetition frequency PRF. The signal reflected off of an object is attenuated in the receiver to the baseband range. By analyzing the baseband signal, the signal propagation time T and possibly the signal Doppler shift f_d are determined. From the propagation time T , the object-sensor slant distance R is derived, ultimately based on the speed of light c from $R = c \cdot T/2$, and the object velocity v , the carrier frequency being f_c from $v = c/2 \cdot f_d/f_c$.

Customary pulsed radar systems use the following operating modes:

LPRF (low pulse repetition frequency):

In this case, pulsed radars have such a low pulse repetition frequency PRF, that a unique measurement up to the greatest desired object distance is always possible. However, if velocities occur that can result in f_d being greater than $PRF/2$, the velocity determination is no longer unique, however.

HPRF (high pulse repetition frequency):

Here, operation takes place at such a high pulse repetition frequency that the velocity determination in the entire relative velocity range is always unique. The distance measurement is only unique when all objects in the detecting range exclusively have smaller distances than $c/(2 \text{ PRF})$ to the sensors.

PRF staggering (staggered PRF):

To avoid so-called blind speeds which occur at constant pulse repetition frequency, or to flatten the line spectrum of the transmitted signal that exists given a constant pulse repetition frequency, e.g., for improved interference suppression, pulse pause intervals of variable length (variable interpulse period VIP) are also used.

Coherent mixing:

To attenuate the received signal to the baseband range, it is customary for the receiver to mix the received signal with a copy of the transmitted signal. Given a spatial proximity of the transmitter and receiver, the copy can be possibly derived from the same oscillator as the transmitted signal or from a second oscillator of the receiver's own. Depending on whether a stochastic relationship exists from pulse to pulse, among the phases of the received signal and its copy, one speaks of incoherent or coherent mixing. The coherent mixing affords a precise Doppler or velocity determination. However, to achieve the desired coherence, for the most part, considerable outlay must be expended to synchronize the phases (use, for example, of lock-pulse methods or digital detectors of the transmission phase). Incoherent methods are usually called for when no

velocity measurement or only an imprecise velocity measurement is required.

Monostatic, bistatic:

5 If the transmitting and receiving antennas are "distinctly" spatially distant from one another, and if the transmitted signal and its copy are derived from different oscillators for mixing purposes, one usually speaks of bistatic radar systems, in contrast to monostatic radar systems.

Pulse compressions:

10 For a pulsed radar to achieve a minimal coverage range, a minimum of total energy is required which must be reflected off of an object and integrated by the receiver. Given a predefined pulse repetition frequency, limited peak power output of the transmitter, and limited permissible integration
15 time, the energy can only be still increased by prolonging the pulse duration. On the other hand, the correlation duration (width of the autocorrelation function) of a pulse determines the attainable resolution of a pulsed radar. By using internal pulse modulation/coding, also referred to as pulse compression
20 methods, the correlation duration (the resolution) and pulse duration (energy and average power output and, thus, instrumented coverage range) can be theoretically defined independently of one another. Customary compression methods are linear or non-linear frequency modulation, as well as
25 biphasic or multiphasic modulation.

From the technical literature, it is known that the most widely varying combinations and hybrid forms of the above mentioned methods are used.

Fields of application of pulsed radars:

Monostatic pulsed radars:

In the military sector and in civilian air-traffic control, in particular, monostatic pulsed radars having substantial transmitting power and antenna directivity (beam focusing) are often used for measuring great distances and, to some extent, high velocities. Frequently, a range and azimuth scan is carried out, as well as a relatively complex Doppler processing (MTI, MTD process), as well as, typically, pulse coding/pulse compression, e.g., chirp and modulation of the pulse repetition frequency (VIP, staggered PRF).

Bistatic pulsed radars:

Bistatic pulsed radars are found, virtually without exception, in the military sector, in astronomy and in meteorology, where the object distances are large and are accompanied by great transmitter and receiver distances (baselines, for example, in the range of hundreds of kilometers). High demands are typically placed on the components of such bistatic radars, particularly due to the requisite time synchronization of the sensors (pulse synchronization for distance measurement, phase synchronization for velocity measurement (Doppler)) over large spatial distances. Also regarded as difficult are the required synchronized alignment of the viewing directions and, in some instances, allowance for platform movements.

Low-cost pulsed radars:

Microwave pulsed radars are increasingly being used in applications where objects are detected at small distances, using low transmitting power and a wide visual range, and where, additionally, low costs are required, such as for door openers, room surveillance, detection of motor-vehicle surrounds fields. Often used in this context are monostatic

LPRF methods, incoherent mixing, no pulse compression, or possibly pulse compression including biphase modulation. In contrast to military radar systems or air-traffic control radars, for the low-cost pulsed radars, high-quality components are rarely used. Rather, oscillators having low frequency stability, mixers and LNAs having low bandwidth and high noise factor are used, for example.

Summary of the Invention

The measures according to the present invention render possible a cross-echo detection and distance measurement when working with bistatic pulsed radars, thus spatially separate transmitting and receiving antennas and carrier frequency oscillators, it being possible for both carrier frequency oscillators of any one transmitter/receiver pair, in contrast to customary bistatic systems, to be run in asynchronous operation, i.e., they do not necessarily have to be frequency-synchronized or phase-synchronized using costly measures.

The device according to the present invention is distinguished from customary bistatic radar applications, in particular by a time-synchronized pulse modulation when working with transmitting and receiving sensors.

The present invention may be advantageously applied in connection with a pulse repetition frequency that is selected in accordance with the low pulse repetition frequency method, in particular a pulse repetition frequency that is selected to be only slowly changeable over time or piecewise constant over time.

It is thus possible to implement a bistatic pulsed radar in the low cost range as well, using low transmitting power to measure small cross-echo distances (given small baselines), and components that are not of high quality. In pulsed-radar

arrays, it may be used to simultaneously measure direct and cross-echo distances. The additional cross-echo distances increase the spatial sampling of the sensor surround, may be used for classifying object contours, and enhance the redundancy of the sensor information.

The time-synchronous pulse modulation of the carriers of adjacent sensors and mixing of transmitted and received signals result in "image signals" having frequency components below half of the pulse repetition frequency PRF. These are referred to in the following as "cross-echo Dopplers". The mid-frequency of such a cross-echo Doppler may be adjusted via the pulse repetition frequency PRF. The power of the cross-echo Doppler supplies a continuous low-frequency signal, thereby rendering possible cross-echo detection and distance measuring.

In addition to the described implementation, a pulse compression may be carried out. A pulse jitter is likewise possible, provided that it is produced in such a way that it is synchronous for both sensors, and that the cross-echo Doppler is still sufficiently band-limited with respect to the downstream analyzing unit.

Brief Description of the Drawing

Exemplary embodiments of the present invention are explained with reference to the drawing, whose figures show:

Figure 1 a time-synchronously controlled pulsed-radar transmitter-receiver pair;

Figure 2 a power density spectrum of the mixed, non-pulsed carriers of adjacent sensors;

Figure 3 a power density spectrum of the mixed, pulsed carriers of adjacent sensors, given a negligible pulse duration;

Figure 4 the power density spectrum of the mixed, pulsed carriers of adjacent sensors, given a not insignificant pulse duration;

Figure 5 the power density spectrum of a real I(Q) signal during cross-echo reception;

Figure 6 a cross-echo Doppler control and analysis in one variant of an embodiment entailing little outlay;

Figure 7 a cross-echo Doppler control and analysis in one variant of an embodiment entailing medium outlay (spectrum analyzer principle);

Figure 8 a cross-echo Doppler control and analysis in one variant of an embodiment entailing substantial outlay (MTD principle);

Figure 9 two transmitting and receiving sensors, including representation of the direct echoes and Doppler cross-echoes, as well as of the cross-echo range scan.

Detailed Description

Figure 1 shows views of two simple, customary pulsed-radar sensors 11, 12, of which top sensor 11 functions as transmitter (Tx), bottom sensor 12 as receiver (Rx). Using their respective carrier-frequency oscillators 21, 22, the sensors generate carrier signals x_1 and x_2 having individual carrier frequencies f_{L01} and f_{L02} . These carrier signals are preferably modulated by the same pulsed source 3 using the 0-1

pulse sequence p, i.e., via modulators 51, 52, pulses are impressed on the output signals of the carrier-frequency oscillators. Of course, a separate pulsed signal source 3 may also be assigned to each of sensors 11, 12. However, this requires synchronizing these pulsed signal sources among one another. This may be accomplished either by using a connecting lead, or otherwise by recovering the transmitter pulse repetition frequency from the received signal and compensating for the phase offset. The phase offset may be determined by utilizing redundancy, since, due to the reversibility of signal paths (S11 \leftrightarrow S12), two cross-echo measurements of an object are normally available, as are possibly existing self-generated-echo measurements of an object. (for example, assuming: Δ =phase lead angle from pulsed signal source 1 to pulsed signal source 2; tofK; cross-echo propagation time from S11 to object K to S12 or return direction; cross-echo measurement from S11 to S12 relative to pulsed signal source 2; tofK21: cross-echo measurement from S12 to S11 pulsed signal source 1; it then holds that: $\text{tofK} = \text{tofK} - \Delta$ and $\text{tofK} = \text{tofK21} + \Delta \rightarrow \Delta = (\text{tofK12} - \text{tofK21}) / 2 \rightarrow \text{tofK} = (\text{tofK12} + \text{tofK21}) / 2$. The signal radiated by the transmitter, once reflected off of an object and subsequently to propagation time (time-of-flight tof), is received by the receiver. Using a delay circuit/delay line 6, the receiver delays pulse sequence p by delay time τ . If adjusted delay τ corresponds to propagation time tof, then in the case that $\tau = \text{tof}$, signal $m = p \cdot x_1 \cdot x_2$ results at the output of mixer 7, to which, depending on the time-synchronous pulse modulation, a transmitted signal, on the one hand, and, a received signal, on the other hand, may be supplied.

This (ideal) mixed signal is itself low-pass filtered, for example, in an analyzing unit 4 of downstream real amplifier 8 and of real mixer 7 itself. The I-signal is then available at the output of the amplifier or of the impedance converter and, in the case of a second mixer which works with the 90° phase-

offset carrier, also a Q-signal, for further low-frequency signal processing. The following describes the spectrum that results for the I(Q)-signal.

1. The mixture (multiplication) of the non-pulsed carriers, see x_1 and x_2 in Figure 1, of two adjacent sensors having average differential frequency $df = f_{L01} - f_{L02}$, would produce a spectrum having band-limited components of around $df = f_{L01} - f_{L02}$ and $f_{L01} + f_{L02}$ (Figure 2). The summed component may be disregarded in the following due to the low-pass characteristics of mixer 7 and amplifier 8. The width of the remaining spectral component around df is determined by the short-term frequency stability of the carrier-frequency oscillators during the pulse integration time. It is important that such a band-limited spectrum also be produced when working with oscillators that are not frequency- or phase-synchronized.

2. The pulse modulation of product $x_1 \cdot x_2$, which ultimately leads to ideal mixed signal m , corresponds to a sampling, the sampling frequency being given by adjusted pulse repetition frequency PRF of the pulse generator. However, in the spectrum, an ideal sampling (δ sampling) leads to a periodic continuation of the spectrum of the sampled signal. Thus, the spectrum distributed around df is mirrored twice into each of frequency intervals $[z \cdot \text{PRF}, (z+1) \cdot \text{PRF}]$, z being an integral number (Figure 3). It should be noted that a band-limited signal is always formed in the frequency range $[0, \text{PRF}/2]$, thus even given differential frequency df , which is substantially greater than pulse repetition frequency PRF (thus given subsampling). In this context, mid-frequency f_a of the "image signal" in $[0, \text{PRF}/2]$ and differential frequency df are interrelated, as expressed by

$$df = n \cdot \text{PRF} \pm f_a \quad (1)$$

n being $\in N_0$ (an integral submultiple between df and PRF). An ideal sampling is more or less provided when the pulse duration is very short as compared to the shortest period duration of the sampled signal, i.e., $T_p \ll 1/df$. If this is not the case, the amplitudes of the repeated spectral components fall off in accordance with an envelope defined by the pulse shape and the not insignificant pulse duration (Figure 4). In the case of a square-wave pulse of length T_p , the envelope is, for example, a $\sin x/x$ characteristic having the first zero position at $1/T_p$.

3. The spectrum of the real IQ-signal falls off markedly above the limiting frequencies of the mixer and amplifier/impedance converter, which are typically substantially lower than differential frequency df and generally resemble a characteristic shown in Figure 5. This limited signal component, formed by a cross echo in the I(Q)-signal and having its essential frequency components below $PRF/2$, is referred to in the following as cross-echo Doppler. A direct echo of an extremely rapidly moving object having corresponding Doppler frequencies around $f_D = df$ would lead to a similar signal.

4. It should be noted that image frequency f_a of the cross-echo Doppler having predefinable pulse repetition frequency PRF (given a slowly changeable time frequency df) in accordance with (1) may always be adjusted to a desired value. In particular, by selectively setting the pulse repetition frequency, it is possible to ensure, on the one hand, that image frequency f_a is always below the limiting frequency of the mixer and amplifier. On the other hand, given parallel reception of direct echoes of the sensor, it is possible to ensure that image frequency f_a is always above maximum Doppler frequency f_{Dmax} . This may be understood as a "frequency-

multiplexing" use of the I(Q)-signal, where the direct echoes and cross echoes are in separate frequency ranges.

An important condition for a distinct separation is, of course, that the local mixing oscillators be short-term frequency-stable to such an extent that the bandwidth of $x_1 \cdot x_2$ is always smaller than $PRF/2 - f_{Dmax}$.

5. Submultiple n and image frequency f_a characterize the momentary differential frequency of a sensor pair for which cross-echo reception exists. Thus, when working with sensor arrays having more than two sensors, where the differential frequencies of all relevant sensor pairs deviate significantly from one another, a transmitter identification is also possible given a parallel reception of a plurality of cross echoes.

The device according to the present invention is characterized, in particular, by the following features:

- synchronous pulsed driving (connecting lead, or by recovering the transmitter pulse repetition frequency from the received signal and compensating for the phase offset);

- using the cross-echo Doppler in I, Q-signals or in signals derived therefrom, below $PRF/2$;

- control/regulation of mid-frequency f_a of the cross-echo Doppler by changing the pulse repetition frequency.

From this refinement, one derives the following advantages/possibilities:

- power measurement (or the like, e.g., amplitude, quasi peak, etc.) of the cross-echo Doppler supplies a continuous low-

frequency signal for cross-echo detection and cross-echo distance measuring;

- for digital further processing, cost-effective sampling of the low-frequency power signal possible, using low sampling rates (determined by object-sensor dynamics and scan rate);

- cross echoes may be analyzed in parallel to direct echoes, since the cross-echo Doppler in the I, Q-signal is placed with the pulse repetition frequency in a separate frequency range (frequency-multiplexing operation);

- a costly phase synchronization of the carriers is not necessary, but a minimum short-term frequency stability (during the pulse integration time) of the possibly free-running oscillators is required;

- no high demands on the bandwidth of the mixers and low-frequency amplifiers (above selectable image frequency f_a);

- the mid-frequency of the cross-echo Doppler may be kept constant via the pulse repetition frequency, e.g., in the case of a drifting carrier-frequency differential (response to temperature changes, etc.);

- active suppression of otherwise sporadically occurring crosstalk, which occurs in sensor arrays in response to unsynchronized operation using a fixed pulse repetition frequency when the cross-echo Doppler, e.g., due to temperature drift of the carrier frequencies, happens to fall within the frequency range of the direct echoes ($0 \dots f_p$);

- indirect monitoring of the carrier frequencies as diagnostic function (built-in test);

- in sensor arrays, a cross-echo transmitter identification is possible by estimating the carrier-frequency differential on the basis of identified cross-echo Doppler mid-frequency f_a , the pulse repetition frequency, and integral submultiple n of the quotient of df and PRF;

- in addition, customary pulse-compression methods may be used;

- cost-effective hardware implementation possible, e.g., variant of an embodiment entailing little outlay in accordance with Figure 6: controllable PRF generator having PLL/DDS, analog bandpass BP and power measurement/half-wave rectifier.

The device according to the present invention entails the following outlay:

- synchronous pulsed driving necessary; (connecting lead, or by recovering the transmitter pulse repetition frequency from the received signal and compensating for the phase offset using redundant measurements);

- for the f_a control, the pulse repetition frequency must be modifiable in small steps. Thus, the steps must be all the smaller, the greater the ratio df/PRF is, and the smaller the bandwidth of a bandpass is selected;

- in the sensor arrays, for each adjacent sensor and $I(Q)$ -signal, the power of the cross-echo Doppler must be determined.

Different variants of embodiments are described in the following.

It is assumed that all variants use customary pulse-radar heads in accordance with Figure 1, i.e., each transmitter includes at least one carrier-frequency oscillator and modulator (or fast-action switch) for pulse modulation; each receiver includes at least one pulse-delay unit, one carrier-frequency oscillator, one modulator (or fast-action switch) for pulse modulation, and one mixer for attenuating the received signal (Figure 1). In a sensor array, each sensor may be composed of a transmitter and receiver having only one carrier-frequency oscillator, which feeds the transmitter and receiver in parallel.

Thus, the proposed device does not require any modification of customary radar heads, as used for monostatic operation, as well. All variants of embodiments have in common a pulse-synchronous driving of all sensors, i.e., of all transmitters and receivers, and a frequency-selective analysis of the I-signals and optionally of the Q-signals. The variants only exhibit differences in the signal processing of the I(Q)-signals.

Variant entailing little outlay (Figure 6)

I- and optionally Q-signals are filtered by analog bandpass filters 31 using constant resonant frequency f_{res} . In this context, using the pulse repetition frequency, an analog or digital control 32 of mid-frequency f_a of the cross-echo Doppler ensures that, in the case of cross-echo reception, maximum power output is always available in the pass range of the bandpass filters. Power estimation y of the cross-echo Doppler is carried out by analog analysis of the bandpass output signal, e.g., simple rectification (half-wave rectifier/square-law detector) and smoothing. For digital

further processing (detection, distance determination, e.g., by scan operation, see detector outputs $c_I(\tau)$, $c_Q(\tau)$, a sampling 33 of signal (y) at a low rate is possible.

Variant entailing medium outlay (Figure 7)

5 Spectrum analyzer principle: I- and optionally Q-signals are mixed (multiplied) with sinusoidal signals by oscillators 42 tuned to a monitoring frequency f_{mon} , e.g., direct digital synthesizer DDS. If mid-frequency f_a of the cross-echo Doppler is close to f_{mon} , a low-pass signal is formed, whose power
10 output, subsequent to low-pass filtering 41, may be estimated analogly or digitally, and analyzed as in the variant entailing little outlay. The advantage of this variant is that mid-frequency f_a does not need to be kept constant, rather that f_{mon} may follow f_a . In addition, the entire spectrum from
15 0... PRF/2 may be monitored for external interference. Moreover, a sampling of a low-pass signal at a low rate is already possible, and thus a narrow digital low-pass filtering and very precise determination of power output.

Variant entailing greater outlay (Figure 8)

20 I- and optionally Q-signals are sampled 61 pulse-synchronously, i.e., at a rate that is equal to the momentary pulse repetition frequency. A digital filtering by a bandpass filter bank then follows, compare Doppler filter banks typical of MTP radars 62, and a digital power output estimation. This
25 corresponds to an estimation of the I-, Q-power density spectrum in sub-ranges or to the entire spectrum, from 0... PRF/2. To this end, a numerically efficient FFT (fast Fourier transform) may also be used. The advantage of this variant is that the power output and mid-frequency of a cross-echo
30 Doppler may be determined very reliably from the spectrum,

even when, initially, there may be no past information available on the mid-frequency (capture or scan mode). There is maximum flexibility with regard to the (digital) fa specification/control. In addition, a reliable detection of interference signals is possible. In sensor arrays, the cross-echo Dopplers of all adjacent sensors may be monitored simultaneously.

Figure 9 illustrates two spaced-apart radar sensors 71 and 72, which are each equipped for transmitting and receiving operation. The direct echoes are denoted by 711 and 721. They are reflected off of wall 8. Object 9 in the nearfield of the radar sensors cannot be detected by these direct echoes. Detection may only be carried out via cross echo 92. Cross echo 91 is reflected off of wall 8. In the cross-echo range scan likewise depicted in Figure 9, cross-echo Doppler 92 first appears, conditionally upon the shorter propagation time. Cross-echo Doppler 91 appears with a delay that is dependent on the propagation time. The analysis of the cross-echo Doppler enhances the spatial sampling in the short range (angular resolution), permits the classification of object contours, and increases redundancy, particularly in the distant range; i.e., on the basis of the two measured values of direct echoes 711 and 721 and of cross echo 91, it is possible to verify that object 8 is actually one contiguous reflection surface. If direct echoes 711 and 721 were to arrive, but not cross echo 91, then it could be a matter of two different objects in the distant range. It should be noted, however, that given a larger object 9, cross echo 91 could be blocked by wall 8. To increase the reliability of redundancy and detection, a cross-echo analysis of more than two radar sensors among themselves is advantageous (sensor array).